

Strangeness Enhancement Scenarios : Fireball or Independent Strings ?

A. Capella

Laboratoire de Physique Théorique et Hautes Energies*
Université de Paris XI, bâtiment 211, 91405 Orsay Cedex, France

Abstract

Due to the long-standing discrepancy between NA35 and NA36 data on Λ production, two drastically different scenarios of strangeness enhancement are still possible. Independent string models, such as the dual parton model, lead to results close to the NA36 data. On the contrary, the NA35 results can only be described by introducing full final state rescattering of the produced particles. The corresponding predictions for central $Pb-Pb$ collisions at CERN energies differ by a factor 3 to 4. Preliminary data on the net proton ($p-\bar{p}$) rapidity distribution in $Pb-Pb$ collisions favor the independent string scenario.

LP THE Orsay 96-30

April 1996

* Laboratoire associé au Centre National de la Recherche Scientifique - URA D0063

Most of the string model attempts to describe strangeness enhancement in heavy ion collisions go beyond the strict framework of independent strings. The modifications consist of string fusion [1-8] and, in most cases, final state rescattering of the produced particles [3-8]. String fusion is quite natural in string models. In particular, in the dual parton model [9] (DPM), string fusion is simulated by $qq\text{-}\bar{q}\bar{q}$ pairs from the nucleon sea [2,3], and, in this way, the string independence is maintained. Final state rescattering, on the contrary, is a drastic departure from independent strings models. When fully effective, it implies that the results of these models can only be used as an initial condition - the final state being strongly modified by the rescattering of the produced particles which drives the system towards equilibrium. The model becomes then similar to the so-called fireball models - such as hadron gas models and models based on the production of a deconfined quark-gluon plasma [10-14].

What do we learn from the confrontation of the string models with the available data ? A first remark is that in the independent string framework (i.e. without final state interaction), the effect of string fusion (or sea $qq\text{-}\bar{q}\bar{q}$ pairs) is numerically small when considering Λ production. Indeed we know experimentally that the ratio $\bar{\Lambda}/\Lambda$ at mid-rapidities is small in heavy ion collisions. In central SS collisions the most accurate value of this ratio is 0.24 ± 0.01 [15] and in SW is 0.20 ± 0.01 [16]. We now know that in $Pb\text{-}Pb$ this value is even smaller : 0.154 ± 0.005 [17]. Since string fusion produces baryons in pairs, it is clear that this mechanism can only affect the Λ yield at 10 % level. The situation is quite different in the presence of final state rescattering. In this case $\Lambda\text{-}\bar{\Lambda}$ pair production from string fusion can be much more important provided a sufficient number of $\bar{\Lambda}$'s annihilate in collisions with nucleons.

Based mostly on NA35 results [18], it is widely accepted that a fireball scenario is the only possible one - either with QGP formation or with full final state rescattering. The only

work where the fireball scenario has been explicitly dismissed [8], uses, in order to describe the data, the VENUS Monte Carlo [7] which actually contains final state rescattering. The HIJING Monte Carlo also used by the authors of [8], which has no final state interaction, does not describe either the NA35 [18] or the NA36 data [19] (see fig. 1c of ref. [8]).

In most analysis, the NA36 data on Λ production are not considered. This is due in part to their limited coverage in p_\perp . At present, NA36 data have been fully corrected for acceptance, efficiency and decay via unseen channels [19]. (Corrected $\bar{\Lambda}$ and K_0^s data are not given). Moreover, they can be extrapolated to the full p_\perp range, or, alternatively, the NA35 data can be restricted to the p_\perp range of the NA36 experiment so that a comparison of the two data sets is possible. It turns out that there is a discrepancy between them which exceeds a factor two [19].

The purpose of this letter is to show that the NA36 data on Λ production can be described in the strict framework of DPM with independent strings. An important ingredient in achieving this goal is the novel mechanism of baryon stopping introduced in ref. [20] - which increases substantially the Λ yield at mid-rapidities. No final state rescattering is needed. When such rescattering is introduced, the Λ yield is increased by a factor $2 \div 2.5$ and agreement with the NA35 data is then achieved. It is also shown that the predictions of these two scenarios for central $Pb-Pb$ collisions are dramatically different and thus a clear experimental distinction will be possible. Moreover, recent preliminary data on the net proton yield ($p-\bar{p}$) in central $Pb-Pb$ collisions [21] give some indirect evidence in favor of the independent string scenario. Indeed, the DPM prediction for this difference, with no final state interaction [20], is in good agreement with these data. The final state interaction $\pi + N \rightarrow K + \Lambda$, which is mainly responsible for the increase of the Λ yield, produces a corresponding decrease in the N one which destroys the agreement between theory and experiment.

We turn now to the calculation of the Λ rapidity distribution in pp , central SS and central $Pb-Pb$ collisions at CERN energies. We proceed in the framework of the dual

parton model [3, 9]. In a first step we switch off the $qq\text{-}\overline{q}\overline{q}$ pairs in the nucleon sea ($\alpha = 0$). Moreover, we also switch off all final state interactions. As discussed in [3] an important drawback of the model is a too small baryon stopping. As a consequence, the rapidity distributions of both proton and Λ in central SS collisions have a pronounced dip at mid-rapidities not present in the data. This problem has been solved in ref. [20] with the introduction of a diquark breaking (DB) component - in which the baryon number follows one the valence quarks and is thus produced closer to $y^* \simeq 0$. Based on ISR data on p and \bar{p} inclusive production near $y^* \sim 0$, it was concluded [20, 22] that this DB component has a cross-section $\sigma_{DB}^{pp} = 7$ mb, and thus its size is about 20 % - the diquark preserving (DP) component, corresponding to the fragmentation of the diquark as a whole, being about 80 %. An important result of ref. [20] is that the DB component increases with A faster than the ordinary (DP) one. As a consequence, the effect of this mechanism on the proton yield in NN and in peripheral SS collisions is rather small - while in central SS collisions it grows larger and has the right size needed to reach agreement with the data. The prediction for central $Pb\text{-}Pb$ is also given in ref. [20]. Recent preliminary data [21] nicely confirm both the plateau height and the shape of this prediction.

With this novel mechanism of baryon stopping the formulae for the Λ rapidity distribution in pp and AA collisions are

$$\frac{dN^{pp \rightarrow \Lambda}}{dy}(y) = \frac{\sigma_{DB}}{\sigma_{in}} \frac{dN_{DB}^{NN \rightarrow \Lambda}}{dy}(y) + \left(1 - \frac{\sigma_{DB}}{\sigma_{in}}\right) \frac{dN_{DP}^{NN \rightarrow \Lambda_L}}{dy}(y) + \frac{dN_{DP}^{NN \rightarrow \Lambda_{NL}}}{dy}(y) \quad (1)$$

$$\begin{aligned} \frac{dN^{AA \rightarrow \Lambda}}{dy}(y) = & \bar{n}_A^{DB} \left[\frac{dN_{DB}^{NN \rightarrow \Lambda}}{dy}(y) \right]_{n=\bar{n}/\bar{n}_A} + (\bar{n}_A - \bar{n}_A^{DB}) \left[\frac{dN_{DP}^{NN \rightarrow \Lambda_L}}{dy}(y) \right]_{n=\bar{n}/\bar{n}_A} \\ & + \bar{n}_A \left[\frac{dN_{DP}^{NN \rightarrow \Lambda_{NL}}}{dy}(y) \right]_{n=\bar{n}/\bar{n}_A} . \end{aligned} \quad (2)$$

Here $\sigma_{DB} = 7$ mb, $\sigma_{in} = 32$ mb,

$$\bar{n}_A^{DB} = A \int d^2b \left[1 - (1 - \sigma_{DB} T_{AA}(b))^A \right] / \int d^2b \sigma_{AA}(b) ,$$

$$\bar{n}_A = A \int d^2b \left[1 - (1 - \sigma_{in} T_{AA}(b))^A \right] / \int d^2b \sigma_{AA}(b) .$$

The profile function is given by

$$T_{AA}(\vec{b}) = \int d^2s \, T_A(\vec{s}) \, T_A(\vec{b} - \vec{s}) \quad .$$

In numerical calculations, a standard Saxon-Woods form has been used. For central collision we take $b = 0$ (taking $b \leq 1$ fm the differences are negligeably small). $dN_{DP}^{\Lambda_L}/dy$ and $dN_{DP}^{\Lambda_{NL}}/dy$ are the ordinary (DP) contributions for leading and non-leading Λ respectively. The corresponding formulae and numerical parameters are given in ref. [3]*. Note that with $\sigma_{DB=0}$ one recovers the expressions of ref. [3]. The DB component is [20]

$$\left[\frac{dN_{DB}^{NN \rightarrow \Lambda}}{dy}(y) \right]_n = C [\tilde{\rho}_{q_v}^n(y) + \tilde{\rho}_{q_v}^n(-y)] \quad ,$$

$$\tilde{\rho}_{q_v}^n(y) \equiv Z \, \rho_{q_v}^n(Z) = Z^{1/2} \int_Z^{1-Z} \frac{dX}{\sqrt{X}} (1 - X - Z)^{n-3/2} \quad . \quad (3)$$

This contribution is proportional to the momentum distribution of a valence quark in a proton - which in DPM is entirely determined from reggeon intercepts [9, 20]. The constant C is determined from the normalization to 0.16. The origin of this value is the following. In a NN or pp collision the Λ average multiplicity is 0.1 [23]. However, in the DB component, strangeness production is enhanced by a factor two, since the s -quark can be produced on either side of the valence quark carrying the baryon quantum number [20]. Since the size of the DB component in pp is about 20 %, we have to decrease by the same amount the Λ normalization in order to keep the average Λ multiplicity in pp collisions unchanged. This leads to the value $C = 0.8 \times 0.2 = 0.16$. Likewise the value of the normalization constant a_Λ in the Λ fragmentation function given in ref. [3] has to be reduced by 20 % - while the corresponding values for $\bar{\Lambda}$, p and \bar{p} are unchanged.

The results for $pp \rightarrow \Lambda$ are then very similar to the ones obtained in fig. 1 of ref. [3] and agree with experiment both in shape and absolute normalization. More precisely, we

* The non-leading Λ contribution is proportional to the number of participants, \bar{n}_A , and not to the number of collisions, because, at CERN energies, the production of Λ - $\bar{\Lambda}$ pairs in strings which do not involve a diquark is negligeably small.

obtain $\langle n \rangle_\Lambda = 0.11$ to be compared with the experimental value $\langle n \rangle_\Lambda = 0.096 \pm 0.01$ [23] and $(dN/dy)_{y^*=0} = 0.017$ to be compared with 0.015 ± 0.005 [24].

The numerical results for central SS and central $Pb-Pb$ collisions are given in the first columns of Tables 1 and 2. For central SS collisions we see that the result is close to the NA36 data. As for central $Pb-Pb$ collisions the prediction for the plateau height is about 8 Λ 's per unity rapidity.

We turn next to the effect of the sea $qq\text{-}\bar{q}\bar{q}$ pairs. The calculation of this effect has large numerical uncertainties discussed in ref. [3]. The values given there correspond to the maximal possible ones. As discussed above, in the absence of final state interaction, the amount of $\Lambda\text{-}\bar{\Lambda}$ pair production due to this mechanism is limited by the ratio $\bar{\Lambda}/\Lambda$. This value is small even at $y^* \sim 0$ [15, 17]. The maximal number of $\Lambda\text{-}\bar{\Lambda}$ pairs computed in ref. [3] would yield much larger values for this ratio. Renormalizing downward this number of $\Lambda\text{-}\bar{\Lambda}$ pairs, in such a way that the experimental ratio $\bar{\Lambda}/\Lambda$ is reproduced, we obtain the results given in the second columns of Tables 1 and 2. As anticipated, the amount of pair production both in SS and $PbPb$ is very small.

We consider next the fireball or hadron gas scenario by introducing final state interaction of the produced particles. In ref. [3] it was argued that the reactions mainly responsible for the increase and decrease of the Λ yield are $\pi + N \rightarrow K + \Lambda$ and $\pi + \Lambda \rightarrow K + N$, respectively. Following [3] the excess of Λ 's is given by

$$\Delta \left[\frac{dN^{AA \rightarrow \Lambda}}{dy}(y) \right] = \int d^2s \frac{dN^{AA \rightarrow \pi^-}}{dy d^2s} \left[\frac{dN^{AA \rightarrow p}}{dy d^2s} - \frac{dN^{AA \rightarrow \Lambda}}{dy d^2s} \right] 3 \langle \sigma \rangle \ell n \left[\frac{\tau + \tau_0}{\tau_0} \right]. \quad (4)$$

The particle densities in the rhs of (4) are those obtained in the model without final state interaction (their explicit forms are given in [3]) and $\langle \sigma \rangle = 1.5$ mb $\tau_0 = 1$ fm and $\tau = 3$ fm. In the calculation one has to divide the $\ell n \tau$ interval into a large number of subintervals (in practice a division into 10 equal subintervals gives a good accuracy). After each subinterval one has to evaluate the new values of the p and Λ densities resulting from the final state interaction. These values have to be used as initial conditions for the next

subinterval and so on. In order to do so, one has to know the decrease in the proton yield associated to the increase, Δ , in the Λ one. If the only strange baryon produced by the final state interaction were Λ 's, the decrease of the proton yield would be $\Delta/2$ - with a similar decrease in the neutron one. However, since Σ^\pm , ... are also produced (totalizing approximately the same excess Δ), we assume that the decrease of the proton yield is also equal to Δ [3]. The results for the Λ rapidity distribution after final state interactions are given in columns 4 and 5 of Table 1 for SS and in columns 3 and 4 of Table 2 for $Pb-Pb$ central collisions. Again, the first of these columns is the result without sea $qq\text{-}\bar{q}\bar{q}$ pairs ($\alpha = 0$ in ref. [3]) and the second one is the result with sea $qq\text{-}\bar{q}\bar{q}$ pairs as computed in ref. [3] ($\alpha = 0.1$)*.

In central SS collision the Λ yield has increased by a factor $2 \div 2.5$ due to final state rescattering and is close to the NA35 data [18]. In central $Pb-Pb$ collisions the final state interaction has produced a dramatic increase in the Λ yield - which is 3 to 4 times larger than the corresponding one without final state interaction. In absolute value this difference ranges from 15 to 23 units. Such a huge difference should be easy to detect experimentally. Data on the Λ rapidity distribution in central $Pb-Pb$ collisions will soon be available. In the meantime, it is important to note that there already exists some indirect evidence in favor of the independent string scenario (i.e. DPM without final state interaction). As already mentioned, preliminary results [21] on the net proton yield ($p\text{-}\bar{p}$) in central $Pb-Pb$ collisions are in good agreement with DPM predictions without final state interaction [20]. It has been shown above that the latter produces a substantial increase in the Λ yield and

* As mentioned above, in the presence of final state interaction, a large $\Lambda\text{-}\bar{\Lambda}$ pair production as the one obtained in [3], can be consistent with the small experimental value of the ratio $\bar{\Lambda}/\Lambda$ due to possible experimental annihilation with nucleons. Since the calculation of [3] with ($\alpha = 0.1$) gives the maximal $\Lambda\text{-}\bar{\Lambda}$ production which is possible from sea $qq\text{-}\bar{q}\bar{q}$ pairs, the number of Λ 's has to be in between the values given in the two columns $\alpha = 0$ and $\alpha = 0.1$.

a corresponding decrease in the N one (about 15 units in central $Pb\ Pb$ at $y^* \sim 0$). The decrease in the number of \bar{N} due to $\pi + \bar{N} \rightarrow K + \bar{\Lambda}$ is considerably smaller. Therefore, as a consequence of final state rescattering, the $p\text{-}\bar{p}$ yield will decrease destroying the agreement between the DPM prediction and experiment.

In conclusion, it should be stressed that even if forthcoming CERN data confirm the DPM prediction without final state interaction (i.e. a Λ plateau height of about 8 units), production of fireballs or QGP droplets remains possible in events rarer than the ones considered here. If this is the case it could affect the production of (anti) cascades and (anti) omegas. However, the confirmation of the DPM prediction with independent strings in central $Pb\ Pb$ collisions at the level of Λ production would be quite striking and would confine the QGP search to a much lower production level.

Table 1

y^*	$(dN/dy)_{no\ fsi}^{SS \rightarrow \Lambda}$		$(dN/dy)_{NA36}^{SS \rightarrow \Lambda}$	$(dN/dy)_{with\ fsi}^{SS \rightarrow \Lambda}$		$(dN/dy)_{NA35}^{SS \rightarrow \Lambda}$
0	0.72	0.78	0.97 ± 0.14	1.5	1.9	2.2 ± 0.3
0.5	0.72	0.77	0.97 ± 0.12	1.4	1.8	2.1 ± 0.3
1	0.71	0.75	0.86 ± 0.10	1.4	1.7	2.1 ± 0.3
1.5	0.67	0.70	$0.76 \pm 0.12^*$	1.4	1.6	2.2 ± 0.3
2	0.61	0.62		1.2	1.3	1.4 ± 0.2

Λ rapidity distribution in central SS collisions at 200 GeV/c per nucleon. Columns 1 and 2 are the values without final state interactions - respectively without and with sea $qq\text{-}\bar{q}\bar{q}$ pairs (see main text). Columns 4 and 5 are the corresponding values with final state interaction. The NA35 values are read from Fig. 11b of [18] and those of NA36 from Fig. 14 of [19] with the p_\perp acceptance correction given in eq. (1) (the value with an asterix is for $y^* = 1.25$).

Table 2

y^*	$(dN/dy)_{no\ fsi}^{Pb\ Pb \rightarrow \Lambda}$		$(dN/dy)_{with\ fsi}^{Pb\ Pb \rightarrow \Lambda}$	
0	7.7	8.4	23	31
0.5	7.4	8.1	22	30
1	6.5	6.8	20	25
1.5	4.9	5.0	16	19
2	2.9	2.9	8.8	9.1

Same as Table 1 for central $Pb\ Pb$ collisions at 160 GeV/c per nucleon.

References

- [1] N. Armesto, M. A. Braun, E. G. Ferreira and C. Pajares, University of Santiago de Compostela, preprint US-FT/16-94. References to earlier papers on string fusion can be found in G. Gustafson, Nucl. Phys. **A566** (1994) 233c.
- [2] J. Ranft, A. Capella, J. Tran Thanh Van, Phys. Lett. **B320** (1994) 346 ;
H. J. Möhring, J. Ranft, A. Capella, J. Tran Thanh Van, Phys. Rev. **D47** (1993) 4146 (the calculations in these papers are based on the DPMJET and DTNUC codes).
- [3] A. Capella, A. Kaidalov, A. Kouider Akil, C. Merino and J. Tran Thanh Van, Z. Physik C, in press.
A. Capella, Phys. Lett. **B364** (1995) 175.
A. Capella, A. Kaidalov, A. Kouider Akil, C. Merino, J. Ranft and J. Tran Thanh Van, Proceedings XXX Rencontres de Moriond, Les Arcs, France (1995).
- [4] QGSM : A. Kaidalov, Phys. Lett. **B117** (1982) 459 ; A. Kaidalov and K. A. Ter-Martirosyan, Phys. Lett. **B117** (1982) 247. For the corresponding Monte Carlo code see N. S. Amelin et al, Phys. Rev. **C47** (1993) 2299 ; N. S. Amelin et al, Nucl. Phys. **A544** (1992) 463c.
- [5] RQMD : H. Sorge, R. Matiello, A. von Kectz, H. Stcker and W. Greiner, Z. Phys. **C47** (1990) 629 ; H. Sorge, M. Berenguer, H. Stcker and W. Greiner, Phys. Lett. **B289** (1992) 6 ; Th. Schnfeld et al, Nucl. Phys. **A544** (1992) 439c ; H. Sorge, Z. Phys. **C67** (1995) 479.
- [6] FRITIOF : B. Andersson, G. Gustafson and B. Nilsson-Almquist, Nucl. Phys. **B281** (1987) 289 ; B. Nilsson-Almquist, E. Stenlund, Comp. Phys. Comm. **43** (1987) 387. In this model the enhancement of Λ and $\bar{\Lambda}$ is essentially due to the final state interaction : A. Tai, Bo Andersson and Ben-Hao Sa, Proceedings of the Strangeness '95 International Conference, Tucson, Arizona (1995).

- [7] VENUS : K. Werner, Phys. Rep. **232** (1993) 87.
K. Werner and J. Aichelin, Phys. Rev. Lett. **76** (1996) 1027.
- [8] V. Topor Pop et al, Phys. Rev. **C52** (1995) 1618. Comments on this paper can be found in M. Gaździcki and U. Heinz preprint IKF-HENPG/1-96.
- [9] A. Capella, U. Sukhatme, C. I. Tan and J. Tran Thanh Van, Phys. Rep. **236** (1994) 225.
- [10] B. Koch, B. Muller and J. Rafelski, Phys. Rep. **142** (1986) 167.
- [11] J. Cleymans, K. Redlich, H. Satz and E. Suhonen, Z. Phys. **C58** (1993) 347 ;
J. Cleymans, D. Elliot, H. Satz and R. L. Thews, CERN TH 95-298.
- [12] J. Lettessier, A. Tounsi, U. Heinz, J. Sollfrank and J. Rafelski, Phys. Rev. **D51** (1995) 3408 ;
J. Sollfrank, M. Gaździcki, U. Heinz and J. Rafelski, Z. Phys. **C61** (1994) 659.
J. Rafelski et al, AIP Proceedings series V330 (1995) 490.
- [13] M. Gaździcki and D. Rhrich, preprint IKF-HENPG/8-95.
- [14] U. Ornick, M. Plmer, B. R. Schlei, D. Strottman, and R. M. Weiner, GSI preprint 95-62.
- [15] S. Abatzis et al (WA94 coll), Phys. Lett. **354** (1995) 178.
- [16] S. Abatzis et al (WA 85 coll), Phys. Lett. **B359** (1995) 382.
- [17] M. A. Mazzoni et al (WA 97 coll), Proceedings XXV International Symposium on Multiparticle Dynamics, Stará Lesná, Slovakia (1995).
R. Lietava (WA97 coll), Proceedings XXXI Rencontres de Moriond, Les Arcs, France (1996).
- [18] T. Alber et al (NA 35 coll), Z. Phys. **C64** (1994) 195.
- [19] E. G. Judd (NA36 coll), Nucl. Phys. A **590** (1995) 291c.
- [20] A. Capella and B. Z. Kopeliovich, preprint LPTHE 96-01, hep-ph 9603279.
- [21] P. Seyboth (NA49 coll), Proceedings XXXI Rencontres de Moriond, Les Arcs, France (1996).

- [22] B. Z. Kopeliovich and B. G. Zakharov, Z. Phys. **C43** (1989) 241.
- [23] M. Gaździcki and Ole Hansen, Nucl. Phys. **A528** (1991) 754.
- [24] K. Jaeger et al, Phys. Rev. **D11** (1975) 2405.